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A holistic evaluation of a typical coast nourishment on the Danish West Coast

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Abstract The case described in this article regards 4.7 km of beach in Ferring, situated approx. 5 km south to the mouth of the Limfjord strait on the west coast of Denmark. In 2005, this section of the beach was nourished with 721,000 m^3 of material in order to protect backshore properties, natural heritages and the recreational value of the beach. After the nourishment, the beach was monitored by levelling profiles on four dates to monitor and track the evolution of the nourished material. Furthermore, laboratory tests involving different gradations of nourishment material are shown which indicate solutions to different kinds of coastal protection strategies, estimate the time in between two nourishments and evaluate the cost of maintaining a beach with a high recreational value for the public.

Keywords Holistic · Coast nourishment · Laboratory tests · Scarp

Value of coastal zones in Denmark

Parts of the Danish West Coast are severely eroded and are at present undergoing coastal erosion. Starting in 1875 around 100 groins has been placed in order to protect the coast line (Kystdirektoratet 2005). This kind of system has not been working too well, so new ways of battling coastal recession, together with a change in the common perception of Nature, were invented and applied. This resulted in the realization of the first coast nourishment back in the early 1970s (Fig. 1).

The coastal landscape in Denmark is characterized by multiple areas of geologic, biologic and recreational interests both at a national and international level (e.g. RAMSAR and NATURA2000 habitats). Recognizing the value of a healthy natural environment, the aims for the future are to ensure the presence of naturally shaped beaches and at the same time to reduce the risk of erosion (Holmgren et al. 2006a, b).

For this reason coast nourishment is used widely along the Danish North Sea coast. This method, invented in the early 1970s, is preferred to solid constructions and nowadays resembles the primary method used by the Danish Coastal Authority for coastal protection. Furthermore, it serves a dual purpose as management tool (Holmgren et al. 2006a, b). Coast nourishment is protecting coastal lands as well as backshore properties (infrastructures, buildings etc.) and preserving natural heritages. The material used for coast nourishment is characterised by a medium grain size (d_{50}) and the gradation U (Pilarczyck 2000). Nevertheless, more and more attention is also being paid to the recreational values of the beaches, i.e. tourism, so that an additional purpose of coast nourishment is to increase the recreational space along the shore, while protecting as well.

Danish people and tourists as well enjoy the beauty of the beaches in many ways: activities like bicycling, horse riding, car driving, fishing, sun tanning, swimming and aquatic sports are common and coexisting on the most beautiful Danish beaches. This is possible mainly because

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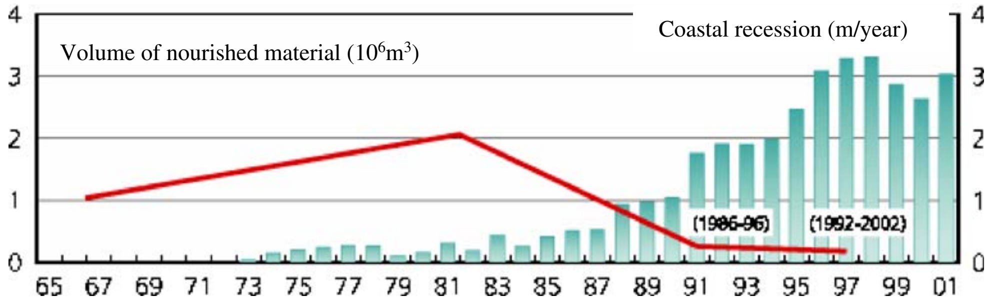

Fig. 1 Volume of coast nourishment (*bars*) applied on coastal erosion (*red line*) 1966–2001 (Danish Coastal Authority 2007) for the 435 km of West cost of Jylland

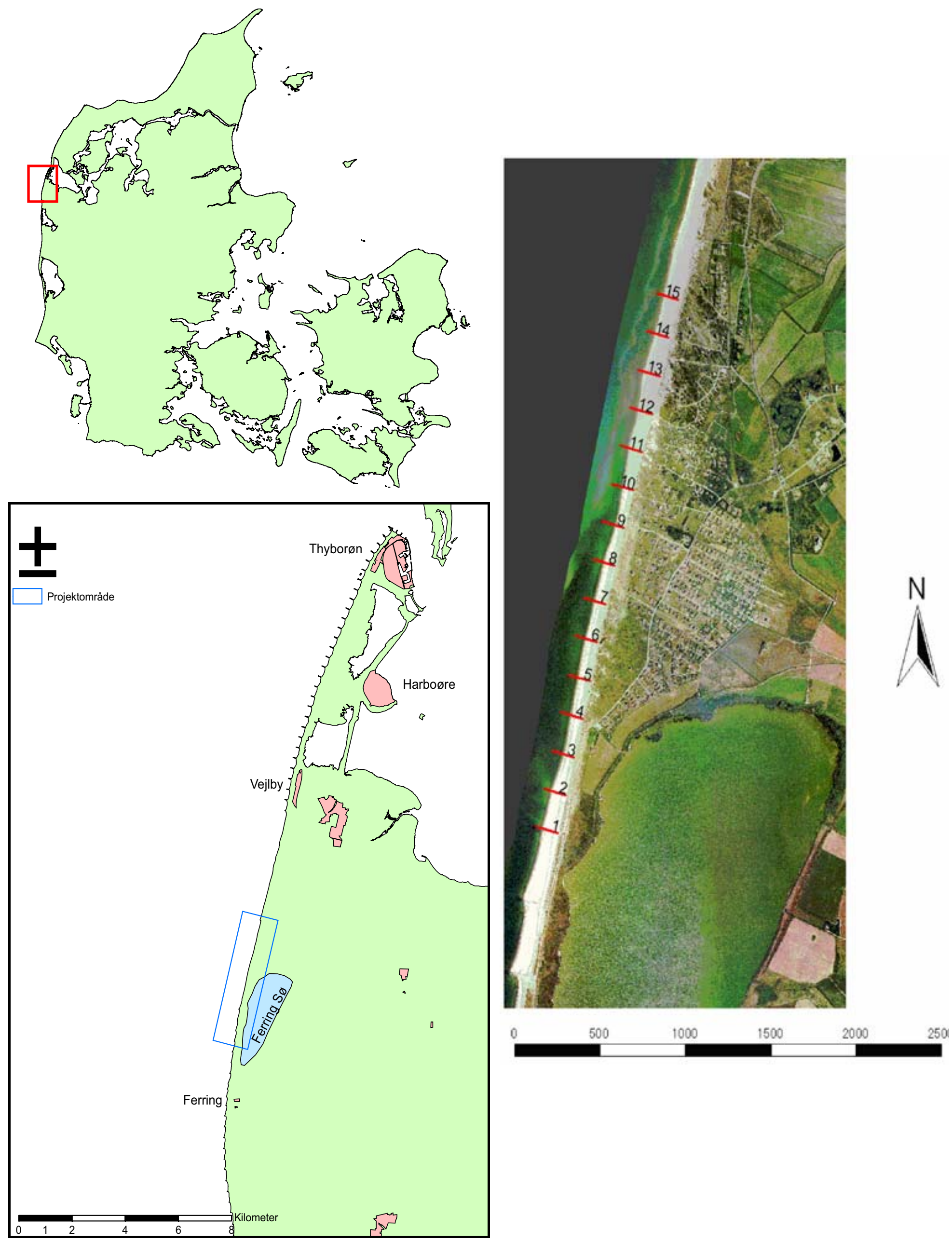

Fig. 2 Zoom of Ferring location, Denmark

Table 1 Offshore wave characteristics at Ferring location

H_s [m]	T_p [s]	Prob [–]
1	5.6	46.8
2	7.0	22.6
3	8.4	10.8
4	9.8	5.1
5	11.2	2.4
6	11.5	0.2

of the natural gentle slopes and wideness of the shore. Therefore, international and national tourism are giving value to the natural heritage of the coast. Nowadays families using the beaches prefer shallow water depths that occur with small grain sizes and gentle slopes.

Seen from a coastal protection point of view it is on the other hand wiser to use coarser materials, and place these materials as close to the dunes as possible. Such a procedure will ultimately lead to the generation of somewhat steep, unattractive and sometimes even dangerous local sandy cliffs, thus modifying the characteristics that are needed to maintain a high recreational value of the coastline.

This paper deals with the holistic problem of coastal protection seen in the light of mechanical stability of coast nourishment and cost effectiveness, and the interest of the public in a coast consisting of fine grained sand for recreational purposes.

Description of the location

In Fig. 2 the site map is presented through a virtual zoom into Ferring location from Denmark to the beach of the nourishment discusses in this article. In the satellite picture the 15 sections related to the measurements have been highlighted. The distance between one and the other is 200 m.

Wave conditions at location are reported on Table 1. The main wave direction is North-West. The data refer to a long term statistic from offshore buoy and they cover more the 87.9% of the total wave conditions at location, with the missing part represented by waves less then 1 m 22.1% of the time. Yearly storm conditions are typically 7 m H_s and 11.5 T_p. In average there are 68 days with $H_s \leq 2$ m in 1 year. There is no tide in this area but a quite severe wind set-up can occur. Statistical data report 1.97 m wind setup as extreme event for 1 year; 2.51 m for 2 years, 2.57 m for 50 years and 2.78 for 100 years.

The natural grain size at location is d_{50}=0.2 mm. For the nourishment a sand worth d_{50}=0.291 mm has been used. More then 348 samples where taken in order to asses this grain size (Frigaard and Wahl 2007). The source of the fill is offshore sand from the same area.

Form Fig. 3 the beach profile in summer 2003 and 2004 and then at the end of summer 2005 right after the nourishment is plotted. The profile covers the linear area from the top of the rear dunes (9 m height at 1,000 m) to −7 m water depth (1,500 m). It is possible to see that before the fill, the beach was 1 m above sea water level with a marked scarp around 1,100 m in 2004. It is also possible to see the evolution of the sandbank (1,300 m–1,440 m).

Beach nourishment at Ferring

Estimating the benefits from the nourishment project requires an estimate of the current economic value attributable to the beach, as well as an estimate on how this value will change if the beach is not nourished. Such a kind of study can be done only by making assumptions.

In our case scenario, a coastal protection plan was strictly necessary and had been adopted due to the severe erosion conditions of the area: an initial nourishment of 721,000 m^3 along 4.7 km of beach was realized at a cost of approx. 2 million Euro in 2005. The nourishment is

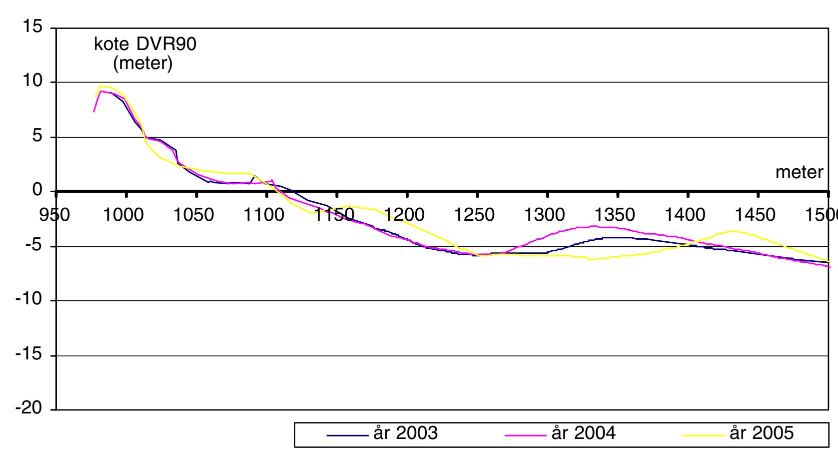

Fig. 3 Profile of the beach in summer 2003, summer 2004 and summer 2005 after the nourishment

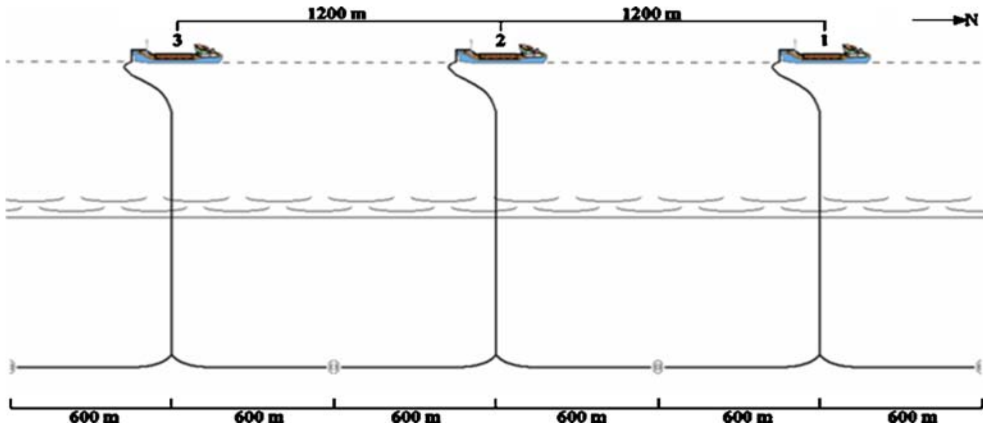

Fig. 4 Sketch of the procedure for beach nourishment

protecting a clear water basin, dunes, private properties and a high value recreational beach.

Figures 4 summarizes the procedure for the nourishment: the length of 4.7 km can be covered with four different placements of the sand-pump dredger. Figure 5 shows the final beach profile. Owing to the inherent characteristics of the applied material and the actual wave climate the nourishment developed into an unwanted cliff.

Figure 6 gives examples of the development of the coast nourishment at Ferring. The top photo shows a nice gentle slope beach with characteristics as wanted, while the two other photos show an example of the unwanted scarp and progressing degradation of the beach.

The unwanted geomorphic feature in which the case study develops (Holmgren et al. 2006a, b), has major consequences on the leisure value of the location, considering the followings; the recreational value of coast nourishment is represented by:

1. the society's willingness to pay a visit to the beach,
2. the increased quality and quantity of beach activities,
3. the natural level of conservation.

These three points can be translated in a number of locally recognized characteristics that a good recreational beach should have in order to allow numerous beach activities:

1. wide extension
2. homogeneous sediment texture
3. fine sediment texture
4. gentle slope to the water

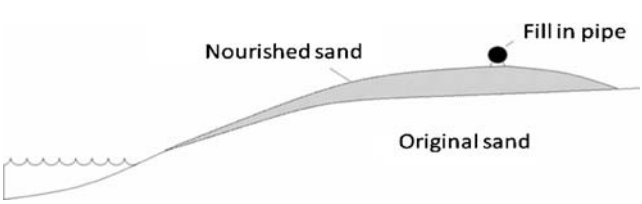

Fig. 5 Sketch of the profile of the nourishment in Ferring. The sand package is thicker in the pipeline surroundings while it becomes thinner as the distance from the pipeline becomes greater

Measurements of the profile of the beach

The profile of the beach has been measured right after the nourishment the 16th of September 2005 and three other times during winter 2005 and the spring of 2006. Those where the 13/12/05, 01/02/06, 13/03/06 and 15/05/06.

The data presented in Fig. 3 show a considerable regression of the shoreline and a reduction of the beach volume of approximately 40 m^3/m after the winter (Fig. 7). The shoreline has been defined as the intersection between

Fig. 6 Beach development: gentle slope leading to the shore generates in a dangerous and undesirable scarp for recreational beach visitors

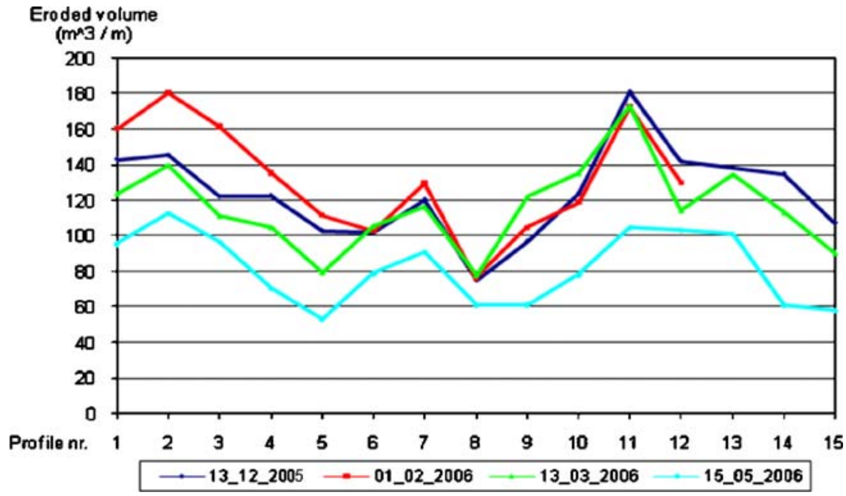

Fig. 7 Regression of the shoreline at Ferring beach

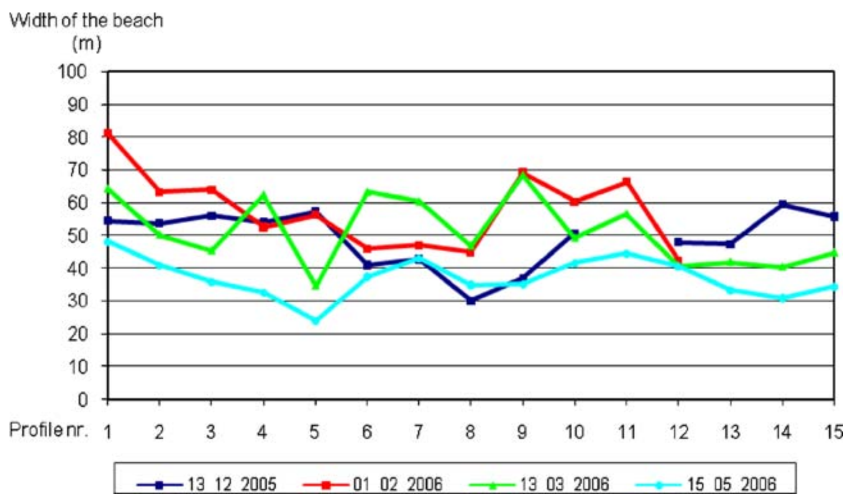

Fig. 8 Shortening of Ferring beach in time

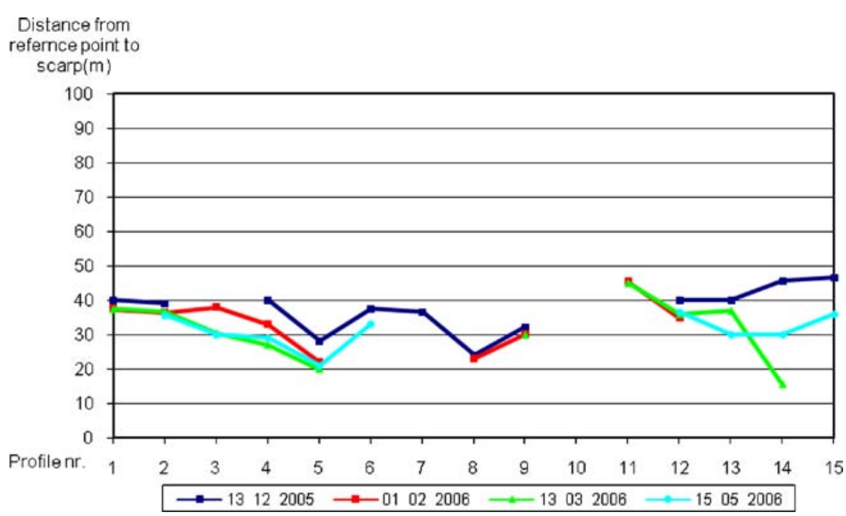

Fig. 9 Movements of the scarp at Ferring beach

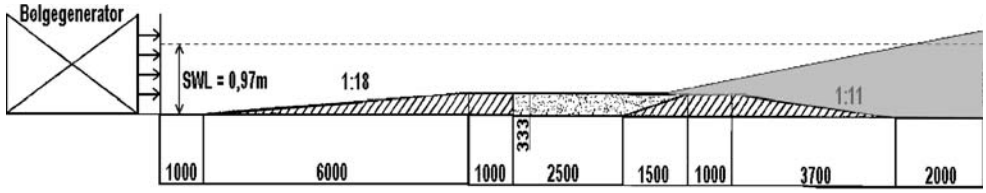

Fig. 10 Flume equipped with wave generator (*left*) and beach settings (*right*) for the experiments (Holmgren et al. 2006a, b)

the measure beach profile and the zero level and the eroded volume is calculated between the shoreline and the scarp.

Due to the existence of several fixed points on top of the rear dunes it was always possible to identify the zero level.

In a condition where 32% of the initial nourishment is lost after a typical winter, its life time is expected to be only 3–5 years. In fact, the beach becomes more and more narrow (Fig. 8) and after such a period, a new nourishment must be planned.

The development of a scarp occurs immediately and the scarp proceeds further inland with the regression of the beach (Fig. 9).

Additionally to the short lifespan of the protection and the fast decrease of the recreational value of the beach, the development of an unwanted scarp and slope is compromising even more the leisure value of the area. The formation of a large scarp is of course related to many factors. The ones that we can have a direct influence on are the grain size and the position on the beach of the nourishment. The question arises how much more it would cost to protect the beach with a nourishment resulting in a smaller scarp? This implies focusing on recreational values more than long lasting (life time) beach protection.

Laboratory tests

Setup

The tests have been realized in an 18 m long and 1 m deep flume equipped with wave generator (Fig. 10). At one end of it the desired profile of the beach was reproduced using layers of different sands in order to simulate the real conditions. Laboratory tests have been made with the purpose of investigating the life time of nourishments exhibiting different gradation at Ferring. This was made by changing the medium grain size distribution (d_{50}) of the sand and the profiles volumes (i.e. initial beach slope). For different wave conditions corresponding to small waves, medium and storm waves, the damage of the protection was been measured and monitored.

Tests

The tests have been run with small, medium and storm waves, corresponding to normal conditions, average storm and severe storm conditions (Table 2). The wave heights were chosen in such a way that the measured erosion corresponds to what was measured in nature in reference scale 1:100. The purpose of the tests was to get knowledge on the correlation between erosion and the formation of the scarp.

The different gradations tested are reported in Table 3, where U is defined as d_{85}/d_{15} and it varies from sample to sample: $2.9 \leq U \leq 6.6$ with average equal to 3.864.

Measurements

Measurements have been done at the beginning and at the end of each test (Fig. 11). A laser profiler mounted on rails on the flume enabled the estimation of the damage to the protection (Fig. 12, left). The laser profiler can plot the results of the profile measurements in real time and constitutes a user friendly interface with the EPro software (AAU 2004b). In a second time it is possible to calculate the damage in terms of lost volumes to the protection (Fig. 12, right). Waves have been measured by wave gauges and generated by AwaSys 5 (AAU 2004a).

Results

General results have been found concordant to established knowledge: a large grain size leads to less erosion but to the development of larger cliffs; the nourishments that gets laid out in a wider area partially in the water (resulting in the

Table 2 Characteristics of the generated waves

Waves	H_s	T_p	H_s (model)	T_p (mode)
Small	1 m	6 s	0.03 m	1.10 s
Medium	3 m	8 s	0.10 m	1.46 s
Storm	6 m	11 s	0.20 m	2.01 s

Table 3 Characteristics of the applied gradations

Sand	d_{50}	U
Fine	0.14 mm	2.72
Medium	0.48 mm	1.32
Coarse	0.66 mm	1.64
Mixed	0.48 mm	4.97

Fig. 11 Profile of the beach before (*left*) and after (*right*) the test (Holmgren et al. 2006a, b)

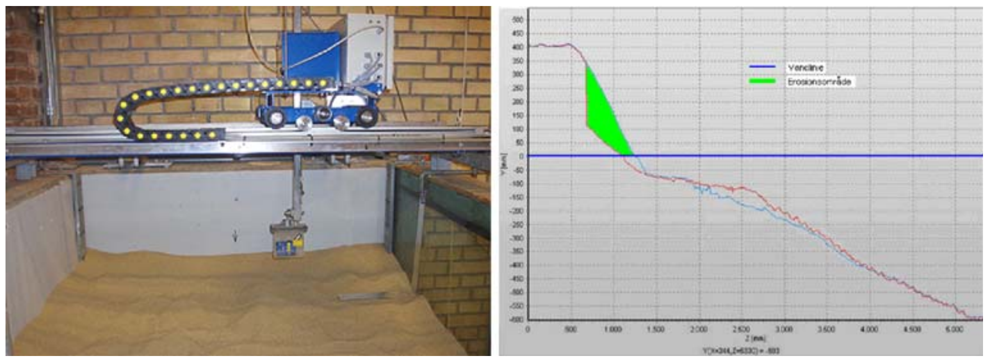

Fig. 12 The laser profile and a measurement of the eroded area (section) (Holmgren et al. 2006a, b)

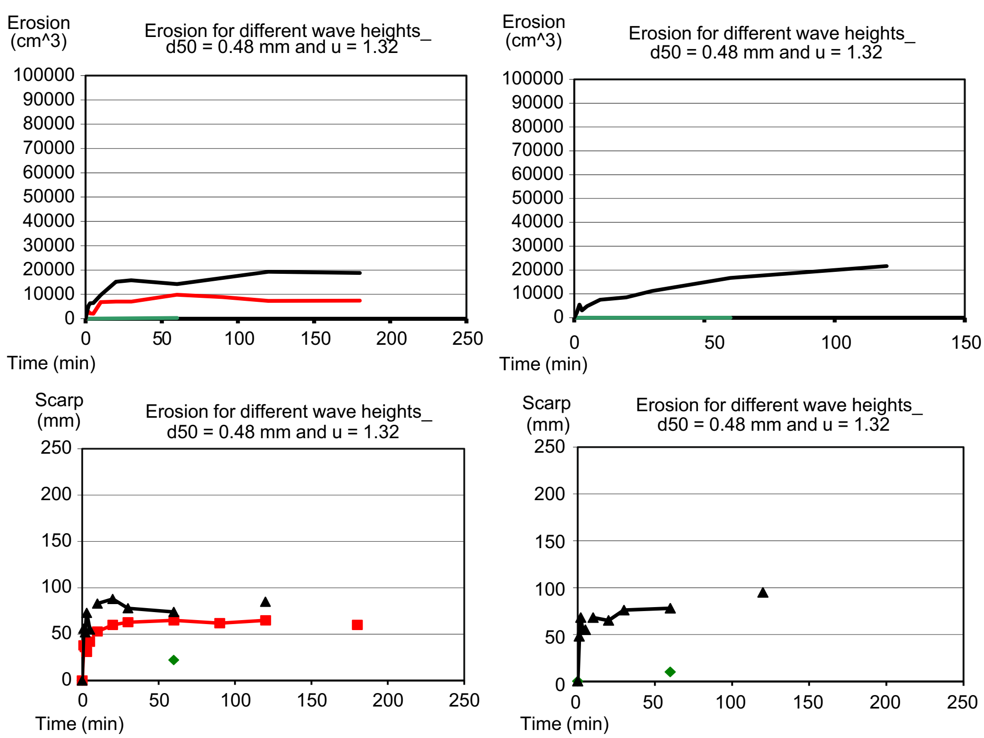

Fig. 13 Laboratory results of erosion in volumes (*top*) and height (*down*) for the beach (*left*) and for the sandbanks (*right*) for a mix sand. The *black line* is for large waves corresponding to storm conditions, the *red* for medium waves and the *green line* or *dots* are for small waves

creation of gentle shore angle) leads to the development of smaller cliffs. The results with mixed sand showed an increased erosion of 12%, while a small decrease of the cliff occurs (12%).

In Fig. 13 the erosion of the nourishment on the beach (left) and on the sandbanks (right) is reported. On the top, the eroded volumes under small, medium and storm wave regimes for the mixed sand nourishment (d_{50}=0.48 mm and d_{50}=1.32 mm in equal parts) appear to increase constantly on the beach. As it is obvious, the higher erosion occurs for storm waves. On the lower graphics, the height of the erosion is plotted against time. It seems as if the erosion of the sandbank reaches the equilibrium before the erosion on the beach.

By comparing the results of the laboratory experiments with field measurements realized during the period between December 2005 and May 2006, a rough quantification of scale effects is made possible. In particular it is noticed that the height of the cliff that occurs in reality in average amounts to 2/3 of the one emerging under laboratory experiment conditions.

The information on scale effects has been used for calculating a more reliable cost of performing a nourishment that minimizes the risk of occurrence of the scarp and exhibits a gentle slope to the waterline. This kind of nourishment implies that bigger volumes of sand must be distributed both on the beach and stretching down into the water (Hallermeier 1978; Birkemeier 1985; Dean 1991). In the other hand it is assumed that there is a maximum amount of sand that can be nourished every time outside the water (present kind of nourishment) and the cost of the protection can then be considered proportional to the volumes of sand.

In Fig. 14 the cost per meter per year of the two different kind of nourishments is plotted; the upper curve represents the cost of nourishment works derived from laboratory measurements of eroded volumes of sand, while the lower one is the estimation that takes into account a correction for scale effects on experimental measured eroded volumes.

It appears that in order to avoid the formation of the scarp, the investment on the nourishment work should be twice the actual investment that actually allows the formation of the scarp up to 1 m height. This cost is estimated to be around 200 Euro par meter par year.

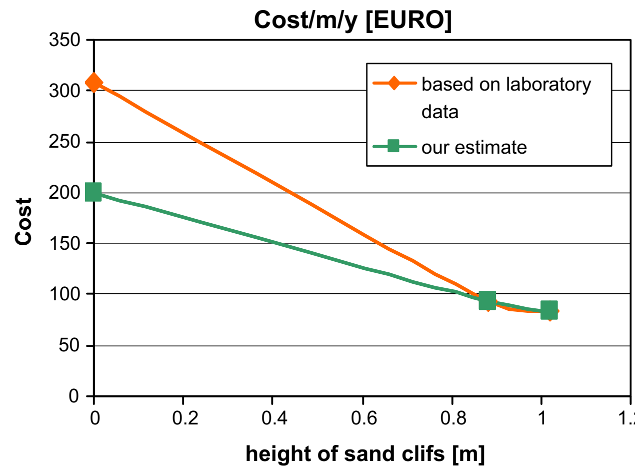

Fig. 14 Cost per meter per year for a more efficient nourishment taking into account scale effects

Conclusions

After field measurements and investigations through laboratory tests regarding a case of coastal nourishment affecting 4.7 km of beach at Ferring on the west coast of Denmark, the following conclusions can be made:

The lifetime of the nourishment characterized by a fill sand of d_{50}=0.291 for a total volume of 155 m^3/m on a distance of 4.7 km is approximately 5 years.

The nourishment is as such that after a winter an unwanted sand scarp is generated.

The scarp develops in size and time and reaches up to approximately 1 m in height during the lifetime of the nourishment.

With progressing erosion the scarp moves further inland.

The scarp compromises the recreational value of the beach while the nourishment still protects the properties further inland.

The use of more spread out nourishment into the water (using larger sand volumes also on the sandbanks, with a gentler slope) generates smaller scarp.

Nourishments with mixed sands generate 12% higher erosion (volume) but some smaller scarp then in the case with uniform sands corresponding to the bigger d_{50}.

The cost of realizing a nourishment that will minimize the formation of the scarp and save the recreational value of the beach is prohibitive.

Aiming to a situation with no scarp (i.e. high recreation value) the estimate cost of the protection is double than the present solution. It is unlikely that he Danish Coastal Authority will afford this cost with the purpose of improving the recreational value of the beach and therefore is concluded that no significant progress is possible.

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